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Entropy generation and natural convection of air under a magnetic quadrupole field in a square enclosure

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Abstract

The natural convection and entropy generation of air are numerically investigated in a two-dimensional square enclosure under a magnetic quadrupole field. In this study. The finite-volume method is applied to solve the coupled equation for flow, energy and entropy generation. Simulations are conducted to obtain solutions in terms of streamlines, isotherms, local entropy generation contours, total entropy generation, Bejan number for various ranges of the magnetic force parameter and Rayleigh number in a nongravitational field. Two symmetric cells with the same strength but opposite rotation directions are observed with the flow filed. Total entropy generation increases with increasing the magnetic force number. However, the average Bejan number holds the reverse trend. The magnetic field has a broad spectrum of applications in engineering areas to control natural convection. The local and total entropy generation presented in this study can be useful addition where one wants to minimize the irreversibility of the system.

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Keywords: Entropy generation; thermomagnetic convection; numerical simulation; magnetic quadrupole field

1. Introduction

An inhomogeneous and strong magnetic field caused by superconducting magnets was proved to induce buoyancy and convection under microgravity, which may lead to airflow generation and promotion of combustion in diffusion flames and so forth[1-2]. Most of the published articles [3-6] related to the thermomagnetic convection of paramagnetic air are restricted, in the thermodynamic point of view, only to the First-law of thermodynamics analysis. The contemporary trend in the field of heat transfer and thermal design is the Second-law of thermodynamics analysis as well as its design-related concept of entropy generation and its minimization. The entropy generation is associated with the thermodynamics irreversibility, which is common in all types of heat transfer processes. Different sources of irreversibility are responsible for the entropy generation such as heat transfer across a finite temperature gradient, characteristics of convective heat transfer, magnetic field effect, viscous dissipation effect, etc. Jery et al

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[7] studied the effect of externally applied magnetic field on the entropy generation and natural convection flow in a square cavity for air and liquid gallium. It was found that increasing inclination angle of the magnetic field tended to decrease the transient oscillatory behavior of entropy generation for air. Bouabid et al. [8] studied the thermosolutal convection in a square cavity filled with a binary gas mixture under an inclined magnetic field. They reported that the magnetic field parameter had a retarding effect on the flow and this led to a decrease of entropy generation. As evidenced from the literature survey, a detailed investigation on the entropy generation of natural convection of air under a magnetic quadrupole field has yet reported in the literature.

The main aim of this work is to analyze the influence of a magnetic quadrupole field on the entropy generation and natural convection of air enclosed in a square cavity. Simulations are carried out for a range of parameters, γRa = 10^4-10^6 and the results are presented in terms of contours of isotherms (θ), streamlines (ψ), entropy generation maps (S_θ and S_ψ) and local Bejan number (Be). The effects of Rayleigh number and magnetic force number on the total entropy generation (S_{total}) and average Bejan number (Be_{av}) are also presented to analyze the relative importance of thermal and fluid flow irreversibilities.

2. Mathematical formulation

2.1. Basic assumption and governing equation

The considered enclosure is illustrated in Fig.1. The system consists of a square enclosure which is kept in a horizontal position and four permanent magnets which generate a magnetic field. The left and right walls are maintained at the uniform temperatures T_h and T_c, where T_h>T_c. The horizontal walls are adiabatic. In the present study, the length of enclosure L, the length of permanent magnet L_1 and the distance of permanent magnets L_2 are 0.024m, 0.02m and 0.03m, respectively.

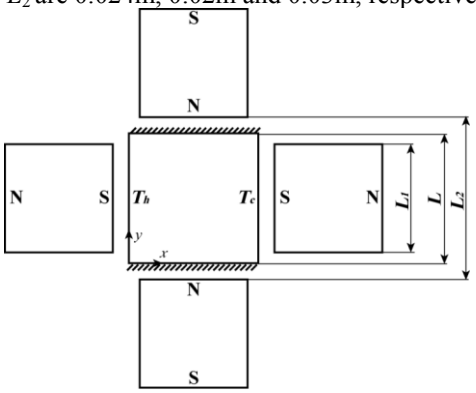

Fig. 1 Physical model and coordinate system

The following assumptions are made in our model: (1) the fluid is Newtonian, incompressible and laminar; (2) all thermophysical properties are constant except the density which varies linearly with temperature in accordance with Boussinesq approximation; (3) the flow field is two-dimensional and steady; and (4) the viscous heat dissipation and magnetic dissipation are sufficiently small to be ignored.

According to Braithwaite et al. [1], the magnetizing force is as follows:

$$\mathbf{f}_{\mathrm{m}} = \frac{\chi_m}{2\mu_m}\nabla\mathbf{b}^2 = \frac{\rho\chi}{2\mu_m}\nabla\mathbf{b}^2 \tag{1}$$

With the above assumptions , the non-dimensional form of governing equations are written as:

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0 \tag{2}$$

$$U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}=-\frac{\partial P}{\partial X}+Pr(\frac{\partial^2 U}{\partial X^2}+\frac{\partial^2 U}{\partial Y^2})-\gamma Ra\,\mathrm{Pr}\,\theta\frac{C}{2}\frac{\partial(\mathbf{B}^2)}{\partial X} \tag{3}$$

$$U\frac{\partial V}{\partial X}+V\frac{\partial V}{\partial Y}=-\frac{\partial P}{\partial Y}+Pr(\frac{\partial^2 V}{\partial X^2}+\frac{\partial^2 V}{\partial Y^2})-\gamma Ra\,\mathrm{Pr}\,\theta\frac{C}{2}\frac{\partial(\mathbf{B}^2)}{\partial Y} \tag{4}$$

$$U\frac{\partial \theta}{\partial X}+V\frac{\partial \theta}{\partial Y}=\frac{\partial^2 \theta}{\partial X^2}+\frac{\partial^2 \theta}{\partial Y^2} \tag{5}$$

The dimensionless variables and parameters in the above equations are defined as

$$X=\frac{x}{L},\quad Y=\frac{y}{L},\quad U=\frac{uL}{\alpha},\quad V=\frac{vL}{\alpha},\quad \mathbf{B}=\frac{\mathbf{b}}{b_0},\quad \theta=\frac{T-T_0}{T_h-T_c},\quad P=\frac{pL^2}{\rho\alpha^2},\quad Pr=\frac{\nu}{\alpha},$$

$$Ra=\frac{g\beta(T_h-T_c)L^3}{\alpha\nu},\quad T_0=\frac{T_h+T_c}{2},\quad b_0=Br,\ C=1+\frac{1}{T_0\beta},\quad \gamma=\frac{\chi_0 b_0^2}{\mu_m g L}$$

where X,Y are dimensionless Cartesian coordinates; U,V are dimensionless velocity components; P is the dimensionless pressure; θ is the dimensionless temperature; T_h is the hot wall temperature, K; T_c is the cold wall temperature, K; Pr is the Prandtl number; b_0 is the reference magnetic flux density, T; Br is the magnetic field intensity of permanent magnet, T; Ra is the Rayleigh number; γ is the dimensionless magnetic force parameter; and **B** is the dimensionless magnetic flux density.

Maxwell's equations are applied to describe the magnetic quadrupole field.

$$\nabla\cdot\mathbf{B}=0 \tag{6}$$

$$\nabla\times\mathbf{H}=0 \tag{7}$$

where **B** is the magnetic flux and **H** is the magnetic field intensity.

Boundary conditions of the problem are given by:

U=V=0 for all walls; θ=0.5 at X=0 and θ=–0.5 at X=1; $\partial\theta/\partial Y$=0 at Y=0 and Y=1

2.2. Entropy generation

According to the local thermodynamic equilibrium of linear transport theory by Bejan [9], the dimensionless total local entropy generation is written as

$$S_G=S_\theta+S_\psi=\left[\left(\frac{\partial\theta}{\partial X}\right)^2+\left(\frac{\partial\theta}{\partial Y}\right)^2\right]+\phi\left\{2\left[\left(\frac{\partial U}{\partial X}\right)^2+\left(\frac{\partial V}{\partial Y}\right)^2\right]+\left(\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}\right)^2\right\} \tag{8}$$

The first term on the right-hand side represents the local entropy generations due to heat transfer (S_θ),while the second term represents the local entropy generations due to fluid friction(S_ψ). The total entropy generation (S_{total}) is obtained by integrating the local entropy generation over the system volume:

$$S_{G,total}=\int_\Omega S_\theta d\Omega+\int_\Omega S_\psi d\Omega=S_{\theta,total}+S_{\psi,total} \tag{9}$$

The Bejan number is defined as the ratio of the heat transfer irreversibility to the total entropy generation, which is written as

$$Be=\frac{S_\theta}{S_\theta+S_\psi}=\frac{S_\theta}{S_G} \tag{10}$$

3. Numerical Procedure

The governing equations are discretized by the finite-volume method (FVM) on a nonuniform grid system. The third-order Quick scheme and the second-order central difference scheme are implemented for the convection and diffusion terms, respectively. The set of discretized equations for each variable are solved by a line-by-line procedure, combining the tridiagonal matrix algorithm (TDMA) with the successive overrelaxation (SOR) iteration method. The coupling between velocity and pressure is solved by the SIMPLE algorithm. The detailed information about the numerical procedure and convergence criterion can be found in our previous work [10].

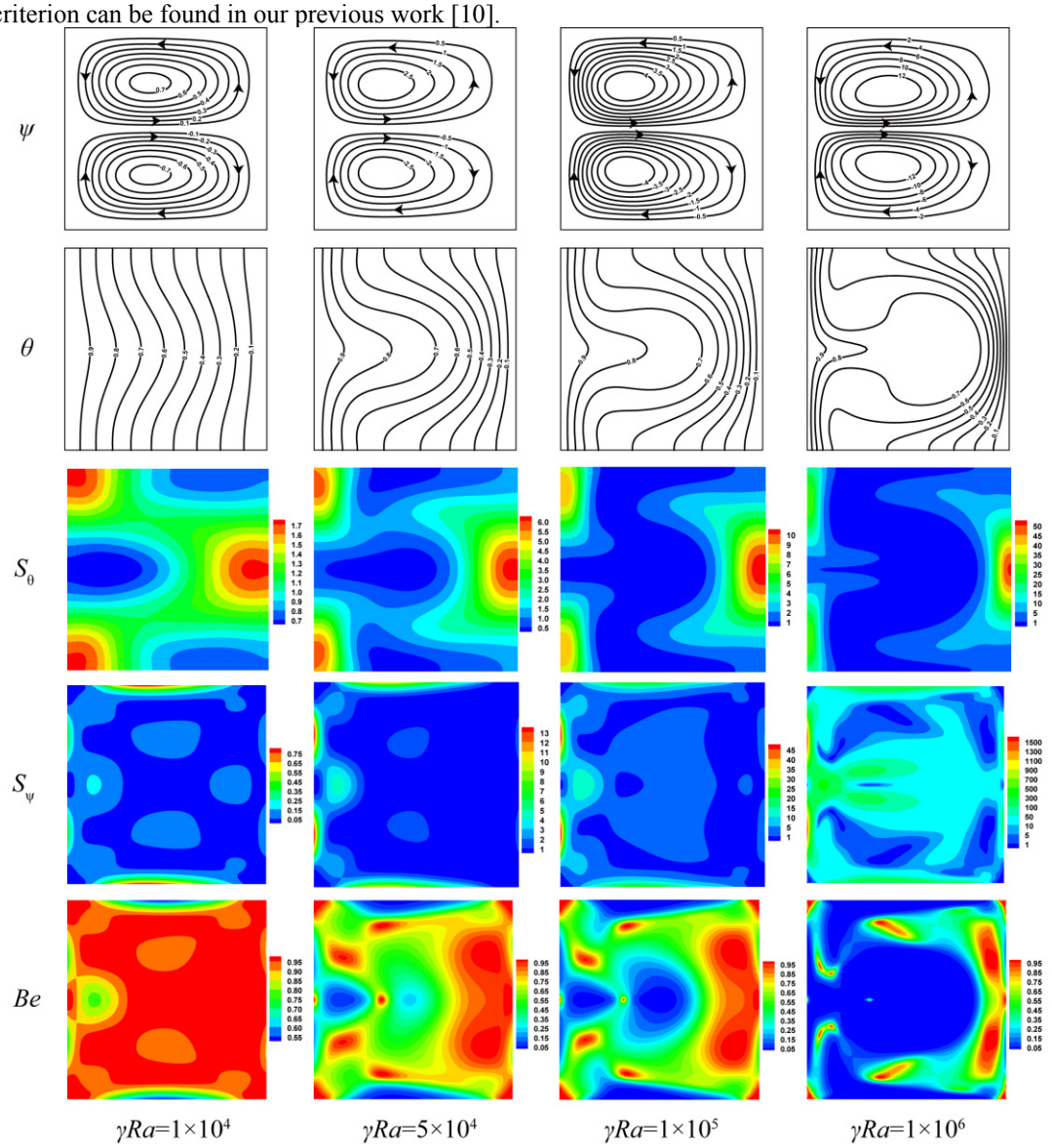

Fig.2 Streamlines (ψ), isotherms (θ), the local entropy generation due to heat transfer (S_θ), entropy generation due to fluid friction (S_ψ) and local *Bejan* number(*Be*) contours for different γRa

4. Results and discussion

The vector of the magnetizing force that is induced by a magnetic quadrupole field has a centrifugal character. It should be pointed out that *Ra* becomes zero and γ becomes infinity when g=0. To circumvent these problems, the finite product γRa has to be used as the governing parameter in the non-gravity cases.

The streamlines, isotherms, distributions of local heat transfer and fluid friction irreversibilities and local Bejan number for different γRa are presented in Fig.2. The distribution of streamlines suggests that there exist two symmetric cells inside the cavity. Among them one is rotating in the anticlockwise direction while the other is in the clockwise direction with the same strength. This characteristic is strengthened with the increase of γRa. For the isotherm contours, they are horizontally symmetric around the middle of the enclosure. Furthermore, they are dense at the top and bottom of hot wall as well as the middle of cold wall. As it can be observed that for $\gamma Ra = 1\times10^4$, isotherms are almost parallel from the hot wall to the cold wall, which shows that conduction dominates heat transfer. When the γRa increased, convection in the enclosure is strengthened and isotherms are largely distorted in the center.

It can be found from the entropy generation map due to heat transfer (S_θ), that S_θ is higher at the top and the bottom left corner of the cold wall as well as at the middle portion of the hot wall due to the high thermal gradient near those regions as seen from the large compression of isotherms. The entropy generation due to the flow friction (S_ψ) is almost negligible throughout the cavity at low γRa. At higher γRa, the S_ψ is high compared to S_θ, with $S_{\psi,max}$=1500 while $S_{\theta,max}$ is only 50.

The distributions of Bejan number are almost symmetric with respect to the horizontal center of the cavity. At lower γRa, the irreversibility due to heat transfer dominates the whole domain except two narrow layers near the top and bottom centers of the adiabatic walls. At higher γRa (i.e. γRa=10^5 and 10^6), convection heat transfer is dominant, and the effect of viscosity flow on entropy generation becomes stronger than that of thermal conductivity.

The variation of total entropy generation (S_{total}) and average Bejan number (Be_{av}) versus γRa are presented in Fig.3. S_{total} increases almost linearly with γRa. It can be explained by the gradual increase of fluid friction irreversibility, in addition to the heat transfer irreversibility, based on the high convection motion of the fluid as seen from contour plots of ψ and S_ψ. Fig.3 (b) illustrates the corresponding average Bejan number (Be_{av}), where a common decreasing trend in Be_{av} with γRa is observed. The maximum value for Be_{av} occurs at the low γRa indicating that the entropy generation in the cavity is primarily due to the heat transfer irreversibility at the conduction dominant mode. At higher γRa, the increment of γRa causes the dominance of fluid friction to entropy generation.

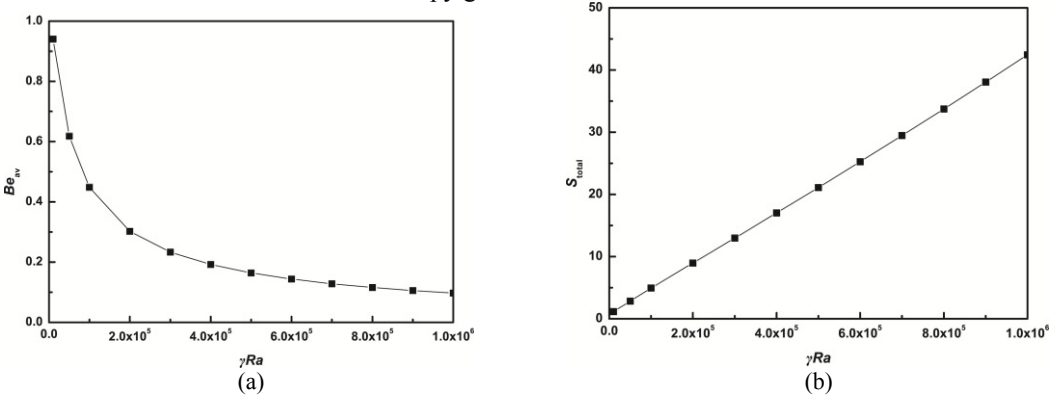

Fig. 3 Variations of total entropy generation (*a*) and average Bejan number (*b*) with γRa

5. Conclusion

The analysis of the entropy generation and heat transfer during thermomagnetic convection of air in a two-dimensional square enclosure under a magnetic quadrupole field in the absence of a gravity field was performed by numerical simulation. The effects of Rayleigh number and magnetic force number were analyzed in detail. For the non-gravity condition, the flow of air in the enclosure is of two cellular structures with horizontal symmetry around the middle of the enclosure. The relationship among the total entropy generation (S_{total}), the Rayleigh number and the magnetic force number can be approximated as a linear increasing function. At lower γRa, thermal irreversibility is more significant and at higher γRa, the flow friction irreversibility is more significant. The result shows that the magnetic buoyancy force has potential applications for enhancing the heat transfer, but this led to an increase of total entropy generation.

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